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FREE-FLIGHT INVESTIGATION OF ABLATION EFFECTS ON THE STABILITY OF CONICAL REENTRY CONFIGURATIONS

C. J. Welsh and G. L. Winchenbach

ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

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FOREWORD

The work reported herein was done at the request of the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC), Wright Patterson Air Force Base, Ohio. The Program Element was 62201F.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-72-C-0003. The tests were conducted from April 15 through June 18, 1971, under ARO Project No. VG0119. Data reduction was completed July 13, 1971, and the manuscript was submitted for publication on October 8, 1971.

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This technical report has been reviewed and is approved.

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ABSTRACT

A 1000-ft aeroballistics range was used to obtain free-flight stability and drag data for slightly blunted 10-deg semiangle cones with and without ablation occurring on the conical skirts. The configurations investigated included ones having fore- and aft-positioned ablation sleeves, as well as one with a skirt material which did not ablate. The investigation was conducted for a Mach number near 14 and a Reynolds number, based on cone length and free-stream conditions, of about 0.55×10^6. Measurements indicate that the forward ablation sleeve configuration investigated had an appreciably larger damping moment than the nonablating cone, whereas the aft sleeve configuration had an appreciably smaller damping moment. Further, the ablating sleeves caused a decrease in the drag coefficient of up to 10 percent, but had no appreciable effect on the static moment and normal-force derivatives.

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NOMENCLATURE

A	Area of the cone base and coefficient reference area
C_D	Drag coefficient
$C_{m_q} + C_{m_{\dot{\alpha}}}$	Damping derivatives, $\dfrac{\partial C_m}{\partial (qd/2V)} + \dfrac{\partial C_m}{\partial (\dot{\alpha} d/2V)}$, 1/radian
C_{m_α}	Static-stability derivative, 1/radian
C_{N_α}	Normal-force derivative, 1/radian
cg	Position of the center of gravity, percentage of cone length from the nose
d	Diameter of the cone base and moment coefficient reference length
I_x	Cone moment of inertia (relative to the longitudinal axis)
I_y	Cone moment of inertia (relative to a transverse axis)
ℓ	Cone length
M	Mach number
m	Cone mass
$\dot{m}$	Time rate of change of the cone mass caused by ablation effects
p	Cone roll rate
q	Cone pitch rate
r_B	Cone base radius
Re_ℓ	Reynolds number based on free-stream conditions and cone length
r_N	Cone nose radius
s	Length of flight interval used in reducing data
V	Cone velocity
α, β	Components of the total yaw angle
δ	$\lvert\beta + i\alpha\rvert$
$\bar{\delta}$	$\sqrt{\overline{\delta^2}}$

$\overline{\delta^2}$	$(1/s)\int_0^s \delta^2\, ds$
ρ	Mass density of the range air
ω	Angular frequency of the yawing motion

SUPERSCRIPT

$\cdot$	First derivative with respect to time

SECTION I
INTRODUCTION

Certain anomalies in the stability characteristics of slender reentry vehicles have been observed in full-scale flight tests, and in some cases these anomalies have been attributed to surface ablation effects. There has been considerable ground testing in the past directed toward examining such ablation effects on the stability of slender cones, see for example, Refs. 1 through 3. Most of the previous experimental programs, primarily in wind tunnels, have involved models having surfaces comprised of material which will ablate at relatively low temperatures or models having porous skins from which gases were ejected to simulate ablation at a rate predicted to simulate the flight case. These are usually referred to as the "ablating surface" and "blowing" techniques, respectively.

It is apparent from the above references that neither technique has been entirely satisfactory. It was noted in Ref. 3, for example, that the use of a low temperature ablator (such as paradichlorobenzene), which was dictated by the low enthalpy wind tunnels involved, resulted in appreciable model shape and mass distribution changes. It can be observed in Ref. 1 that the blowing technique has inherent restrictions in simulating the axial and circumferential distributions of the ejected gas which would occur under actual flight conditions, particularly for a body experiencing oscillatory motion.

In consideration of the limitations in previous ablation testing, a series of free-flight tests has been made for AFFDL in the von Kármán Gas Dynamics Facility (VKF), AEDC 1000-ft Hyperballistic Range G. These tests, of slightly blunted 10-deg semiangle cones, were made at a Mach number slightly less than 14, and at a Reynolds number, based on cone length and free-stream conditions, of about 0.55×10^6. The cones were equipped with ablation sleeves (Delrin®) and with nose tips constructed of Fansteel 60®. The range, as a high-enthalpy, high-pressure test facility, permitted the use of Delrin for realistic mass transfer rates on the skirts. The use of Fansteel 60 nose tips resulted in no appreciable nose shape changes for the above test conditions. This was desired because it was believed that nose ablation might confuse or conceal the effects of skirt ablation which represented the primary goal of the investigation.

SECTION II
APPARATUS

2.1 RANGE

Range G consists of a 10-ft-diam, 1000-ft-long tank that is contained within an underground enclosure (see Fig. 1, Appendix I). It is a variable-density aerodynamic range and contains 53 dual-plane shadowgraph stations. Forty-three of the stations are positioned at nominal 20-ft intervals, yielding an 840-ft instrumented length. The spacing of the other stations is such that a station is located approximately 10-ft downrange of stations 5, 6, 7, 8, 9, 10, 12, 13, 15, and 16. The angular orientation and position of most test configurations can be determined to within approximately ±0.25 deg and ±0.002 ft, respectively, at each station. A chronograph system measures intervals of flight time to within $\pm 2 \times 10^{-7}$ sec. The range vacuum pumping system provides range pressures from 1 atm down to about 20 μHg. The nominal operating temperature of the range is 75°F. The launcher used in this investigation is a two-stage, light-gas gun having a 2.5-in.-diam launch tube.

2.2 CONES AND SABOTS

A series of 10-deg semiangle cones with and without Delrin ablation sleeves were investigated. Delrin, an acetal resin made by polymerization of formaldehyde (CH_2O), is believed to have represented a realistic heat shield material. The cones had a nominal base diameter of 1 in. and a designed nose-to-base radius ratio (r_N/r_B) of 0.07. All of the cones were equipped with Fansteel 60 nose tips. Sketches of the sleeve configurations are shown in Fig. 2 and indicate the fore and aft locations of the Delrin sleeves; the nominal thickness of the sleeves was 0.025 in. A photograph of the sleeve configurations is shown in Fig. 3, and the measured mass and mass distribution characteristics of the individual cones are listed in Table I (Appendix II).

Two pins were inserted into the base of the cones parallel to and equidistant from the longitudinal axis of the cone. These pins (0.06- and 0.04-in.-diam) protruded from the base about 0.07 in. The use of such pins provided a means for obtaining the roll orientation and, in turn, the cone roll rate as a function of downrange distance traveled.

A photograph showing the four-component sabot utilized in the present investigation is shown in Fig. 4. The sabots were constructed of

Lexan® and all of the cones were launched in an uncanted orientation relative to the sabot. The initial angular disturbances to the cones were those arising from muzzle effects and from the cone-sabot separation process.

SECTION III
PROCEDURE

3.1 TEST CONDITIONS

The present investigation was made in air at $13.3 \leq M \leq 13.9$ and at a Reynolds number, based on cone length and free-stream conditions, of about 0.55×10^6. This Reynolds number corresponds to the condition of a laminar boundary layer over the complete length of the non-ablating cone. Test conditions for individual shots are listed in Table I.

Calculations using the method of Ref. 4 indicated that the Delrin sleeves achieved a near-steady-state ablation condition early in the range flights for the above test conditions. The ablation rate of the Delrin sleeve material could be estimated with a good degree of certainty for the present tests because of the availability of Delrin data derived from arc-jet testing reported in Ref. 4. A calculation method is also available in Ref. 4 to estimate the ablation rate coefficient for a sharp cone made entirely of ablating material. Using this method, a value of the coefficient, $\dot{m}/\rho VA$, of 0.0128 was computed for a Delrin cone at the present test conditions.

Ablation rate coefficients were also estimated for the specific sleeve configurations of the present test. The estimate incorporated the surface heat-transfer distribution for the actual, slightly blunt 10-deg cone at zero angle of attack from the equilibrium, real-air computer calcualtion method of Ref. 5. Properties of air from Ref. 6 were used in the calculation which also incorporated the heat blockage term and the Delrin properties of Ref. 4. The following results were obtained:

Configuration	$\dot{m}/(\rho VA)$	$(\rho_w v_w)/(\rho_e u_e)$
Fore Sleeve	0.0084	0.00089
Aft Sleeve	0.0075	0.00066

where $\rho_w v_w$ is the ablation product mass flux per unit surface area and $\rho_e u_e$ is the inviscid, sharp cone (perfect air) boundary-layer edge

momentum. These ablation rates correspond to a sleeve radius recession of less than 0.001 in. in the time of flight along the range; hence, any effects of surface geometry changes on the presented measurements are believed to be negligibly small.

The Fansteel 60 nose tips were utilized in the present investigation to aid in minimizing nose tip ablation. Typical laser-lighted photographs of a cone in flight are shown in Fig. 5. Examination of laser-lighted photographs indicated that no change in the nose geometry of the cones during flight was detectable within the present measuring capability which is estimated to be ±0.005 in. Effects of nose shape changes on the presented measurements were estimated to be well within the data precision.

3.2 DATA REDUCTION

Most of the aerodynamic data were derived from the measured motion histories of the cones in free flight by means of the tricyclic data reduction procedures outlined in Ref. 7. These procedures assume linear variations of force and moment with yaw angle; hence, any nonlinearities in the force and moment data result in "effective" derivatives being obtained.

The angular motion histories of the models were also analyzed by using a nonlinear motion fitting program. This program is a modification of a three-degree-of-freedom motion fitting program referred to as "ANGLES" that was obtained from the General Electric Company (GE), Burlington, Vermont. The GE program uses the approach of Ref. 8 which employs numerical solutions to the equations of motion. Our modifications of the GE program consisted of writing the nonlinearities of the forces and moments involved as functions of the total yaw angle of the cone and including additional terms to extend the program to a quasi six-degree-of-freedom program. The damping derivatives are the only data presented herein that were reduced with the modified GE program. These damping derivatives are equivalent linear values, but the use of the nonlinear program here is significant as the program accounts for amplitude effects, on the motion of a vehicle, caused by the presence of a nonlinear restoring moment. The amount of amplitude decay associated with the shots was, in general, too small in conjunction with the small nonlinearities of the present tests to permit evaluating nonlinear static moment derivatives adequately.

3.3 PRECISION OF MEASUREMENTS

The following table lists the estimated imprecision of measurements. The estimates are primarily based upon repeatability of measurements observed during previous similar range tests.

Coefficient	C_D	C_{m_α}	$C_{m_q} + C_{m_{\dot{\alpha}}}$	C_{N_α}
Estimated imprecision	±0.0015	±0.0045	±0.4	±0.1

SECTION IV
RESULTS AND DISCUSSION

4.1 STABILITY AND DRAG DATA

The damping derivatives ($C_{m_q} + C_{m_{\dot{\alpha}}}$) are presented as a function of Mach number in Fig. 6. Also shown, for comparison purposes, are damping data for nonablating 10-deg cones obtained from range tests reported in Ref. 7. The measurements indicate that the fore ablation sleeve configuration had an appreciably larger damping moment at $M \approx 14$ than the nonablating cone, whereas the aft ablation sleeve configuration had an appreciably smaller damping moment. It is of interest to note that the damping level for the nonablating cone of the present tests is consistent with the previous measurements, which indicate that a large increase in damping at the higher Mach numbers can be expected for such configurations.

It is of interest to observe the measured angular motion patterns shown in Fig. 7. The motion pattern of Shot No. 5 (an aft sleeve configuration) indicates a motion reversal, whereas the patterns of the other four shots are more conventional for nonablating bodies. Reversals in the yawing motion of bodies having large roll rates have been observed in the past and explained by the presence of Magnus moments. Results obtained from motion fits of the present flights indicate the presence of non-zero Magnus-type moments. Although the magnitude of the derivatives associated with the Magnus-type moments are not meaningful, considering the near-zero roll rates of the present cases, the Magnus-type moments are believed to be realistic and to be associated with ablation. It can be observed from Table I that the cone frequency for Shot No. 5 was 0.6 of the frequency level of the other shots; hence Shot No. 5 would have an appreciably different phase angle. Phase angle as used here refers to the phase angle between the oscillatory rate of ejection of the

gases from the ablating surface of a vehicle and the angular motion of the vehicle. The real significance of the phase angle associated with an ablating vehicle in relation to the damping characteristics of its motion is an area that is not sufficiently understood and warrants further attention. The difference in the damping derivatives for the two fore sleeve shots (Fig. 6) is believed to be associated with the sensitivity of the damping moment to the amplitude and type of motion involved in the case of an ablating vehicle.

Prediction of damping derivatives is difficult at high Mach numbers, even for nonablating bodies (see Ref. 7). Hence, it is significant that the simplified analytical approach of Ibrahim of Ref. 9 predicts (assuming a phase lag angle) the same direction of changes in damping associated with fore and aft ablation sleeves as measured in the present investigation. An obvious limitation in the approach of Ref. 9 is the requirement of knowing the phase angle of the ablating configuration involved. At present, computing the phase angle of a vehicle adequately is a difficult task.

The static moment and normal-force derivatives are presented in Fig. 8 as a function of mean amplitude. These are equivalent linear values for the amplitude levels experienced and indicate that any ablation induced effects on either C_{m_α} or C_{N_α} were small. Newtonian levels for C_{m_α} and C_{N_α} are also shown in Fig. 8.

Drag coefficient as a function of the mean amplitude squared is presented in Fig. 9. The measurements indicate that both ablating sleeve configurations had lesser drag than the nonablating cone; the fore sleeve configuration had the larger change in C_D, a decrease of approximately 10 percent. The predicted total drag coefficient and components for the nonablating cone are also shown in Fig. 9. The ablation induced effect measured on a total drag coefficient is normally assumed to be approximately equal to the change in the friction drag coefficient. In the present case the measured decrease in drag would correspond to about a 50-percent decrease in the friction drag coefficient.

There is always concern in an investigation of this type, regarding whether the test results are representative of steady-state ablation conditions. The best check available on the presence of nonsteady-state ablation effects in the present investigation was obtained from examining Shot Nos. 4 and 5 that had nearly constant amplitude motion. Differences in the drag coefficients obtained from sectional fits of the motion histories of these two shots (motion fits of first and last portions of the flights) were negligibly small which indicated that any effects related to nonsteady-state ablation on C_D were also negligibly small.

Realistic comparisons of the present measurements with previously obtained ground ablation data are unfeasible because of differences in configurations and test conditions of the previous tests. However, it is noted that prior damping measurements, involving the ablating-surface technique, have, in general, indicated that ablation over the forward portion of a body caused an increase in the damping (see, for example, Ref. 3).

4.2 COMMENTS ON GROUND TESTS

There has been considerable concern as to how to relate results of ground ablation tests to full-scale flight conditions. This concern is in addition to the scaling problems usually involved in ground testing and is associated with the time lag in the thermal response of ablating materials. This time lag is directly related to the phase angle problem noted above. It appears, in consideration of the present data, that range tests in which different ablating materials are examined at different frequency levels could be particularly useful in evaluating the significance of a phase angle on damping effects associated with an ablator.

SECTION V
CONCLUDING REMARKS

A free-flight range investigation of ablating surface effects on the stability and drag of 10-deg semiangle cones was made. Measurements were made at $M \approx 14$ and at $Re_{\ell} \approx 0.55 \times 10^6$. The measurements indicate that the fore ablation sleeve configuration investigated had an appreciably larger damping moment than the nonablating cone, whereas the aft ablation sleeve configuration had an appreciably smaller damping moment. Further, the ablating sleeves caused a decrease in the drag coefficient of up to 10 percent but caused no appreciable effect on the static moment and normal-force derivatives. It appears that the thermal response time lag associated with ablating materials is a problem area that can be studied further by examining cones coated with different ablating materials and tested at different frequency levels.

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APPENDIXES

I. ILLUSTRATIONS
II. TABLE

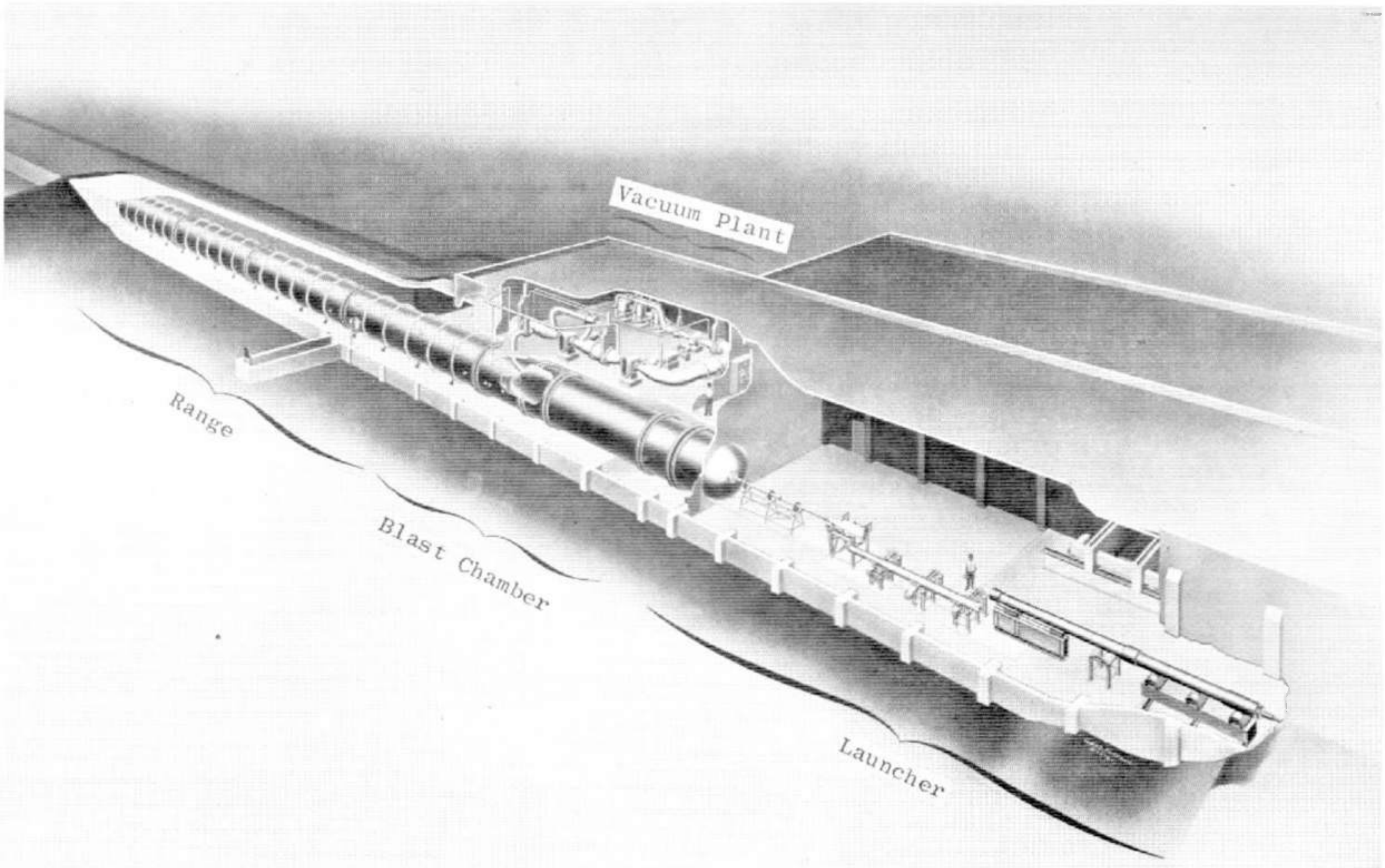


Fig. 1 Range G

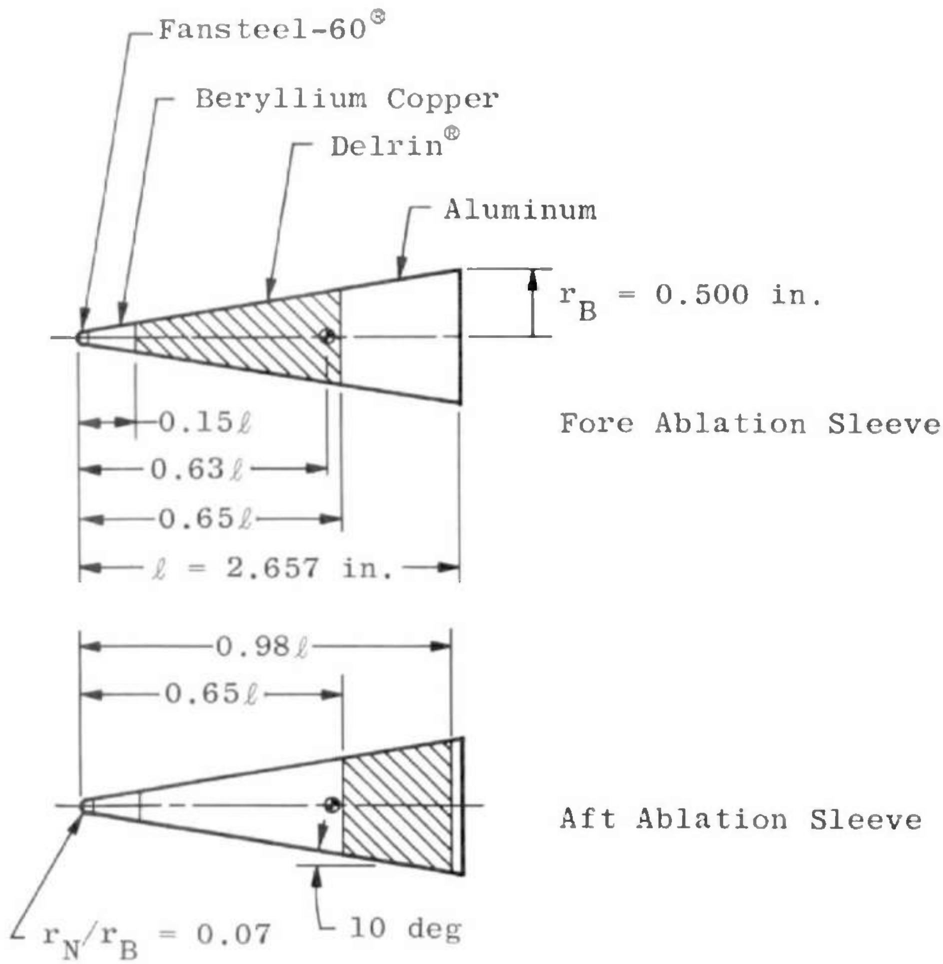


Fig. 2 Fore and Aft Ablation Sleeve Configurations

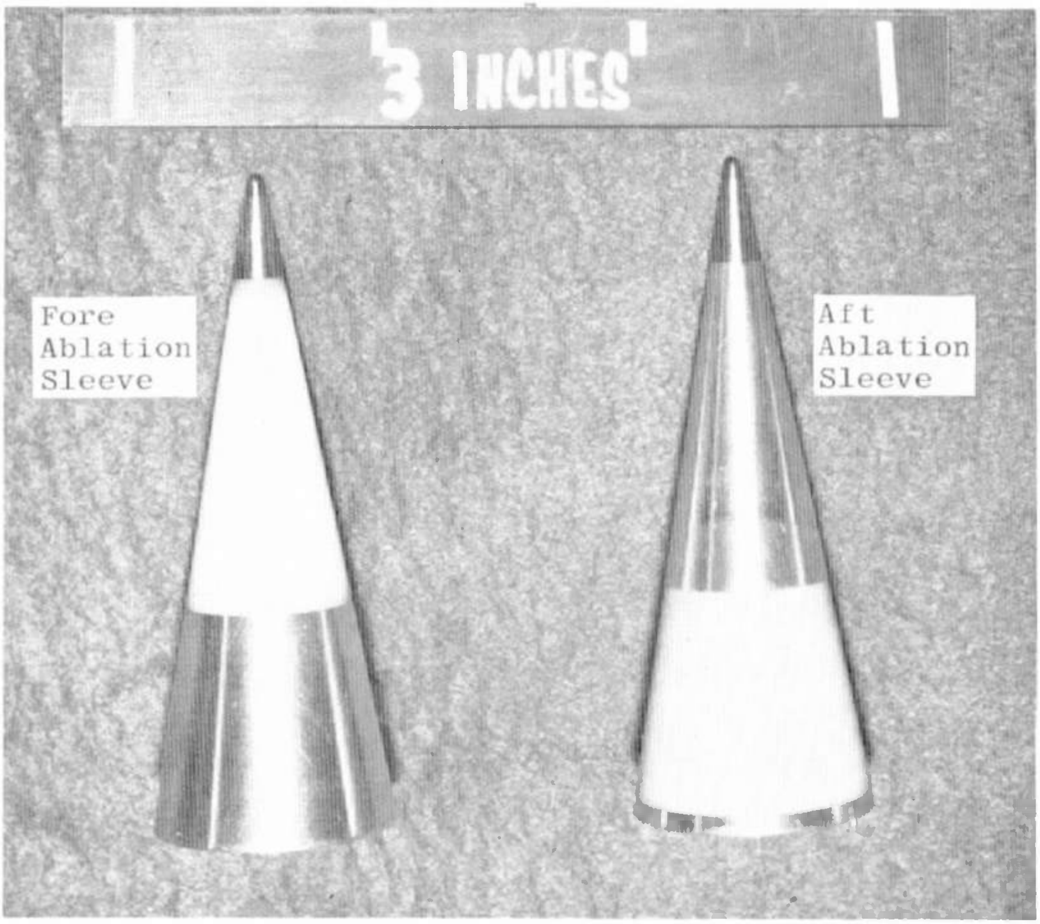


Fig. 3 Photographs of the Fore and Aft Sleeve Cones

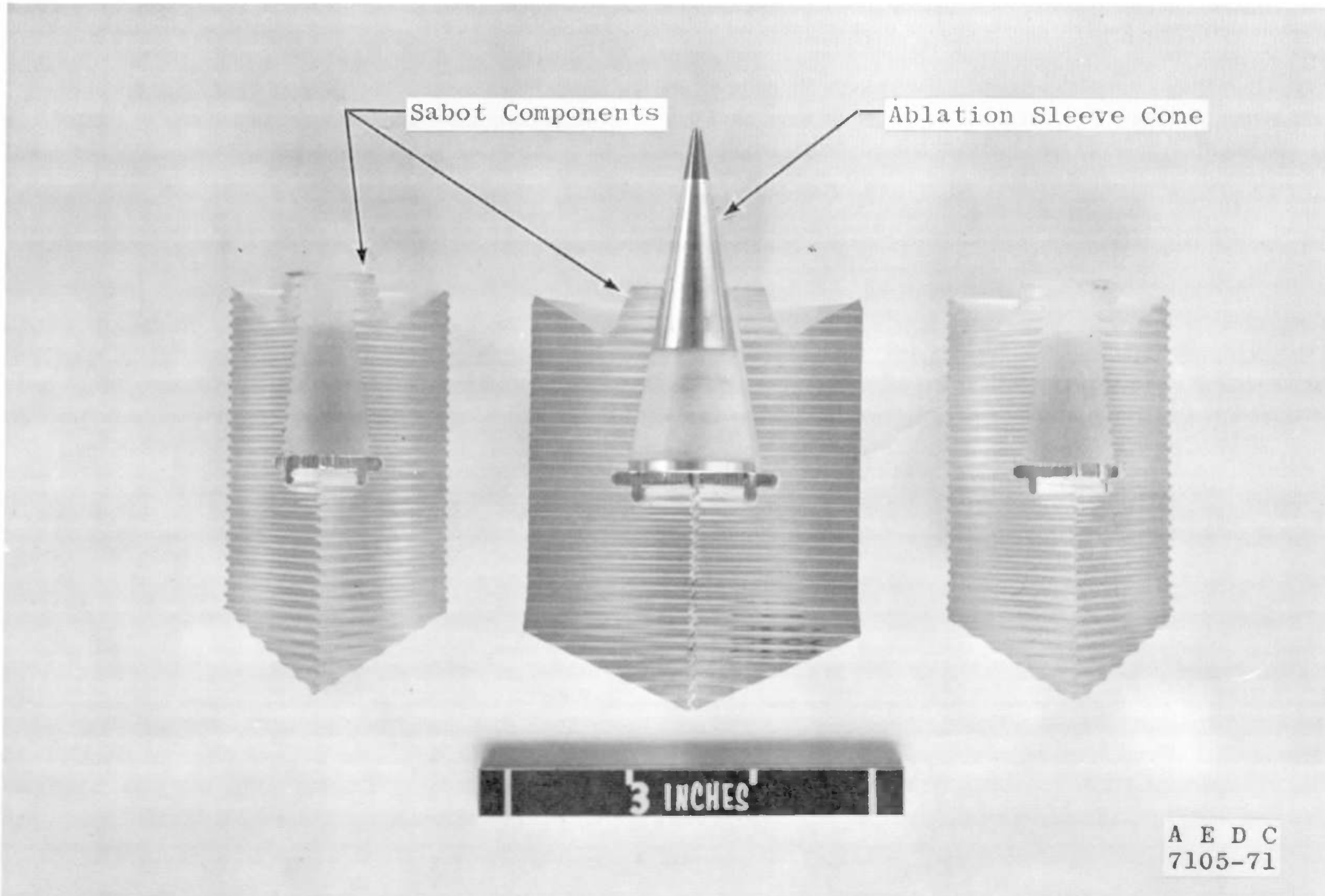
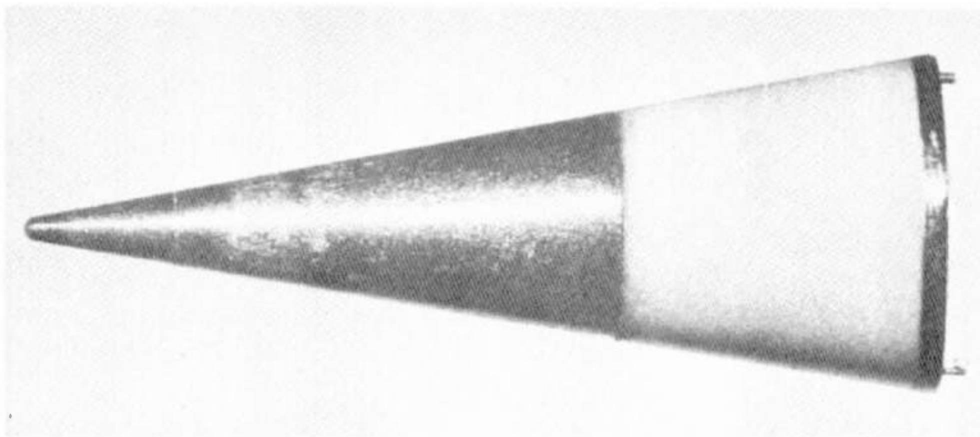
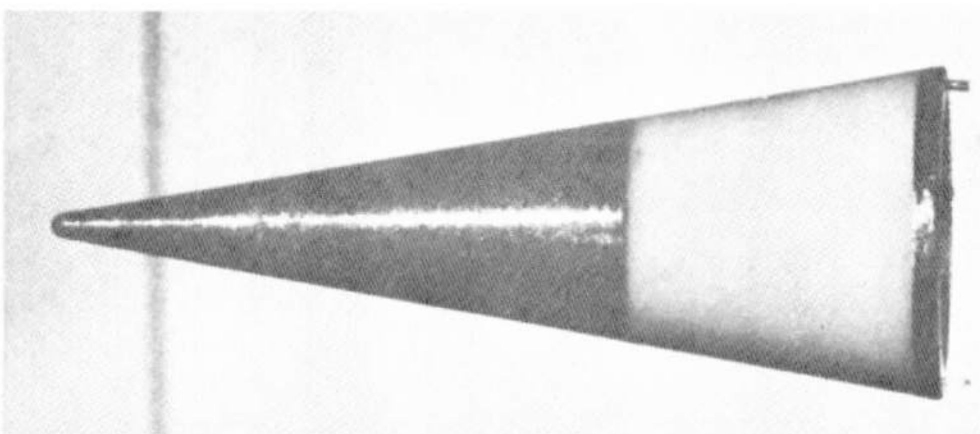


Fig. 4 Photograph of a Cone and Sabot Components



a. Near the Start of the Flight



b. Near the End of the Flight

Fig. 5 Laser-Lighted Photographs of an Aft Ablation Sleeve Cone in Flight

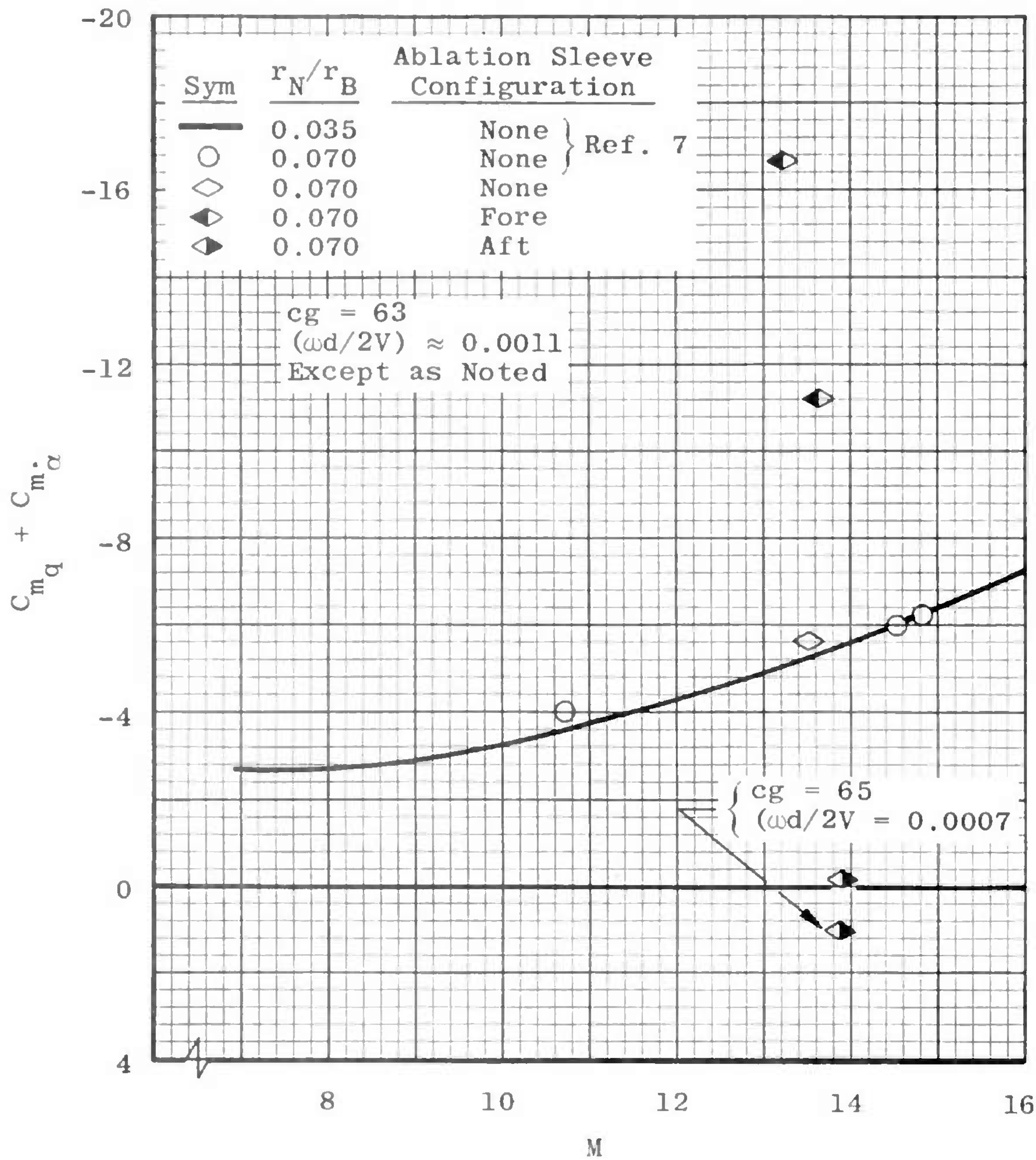
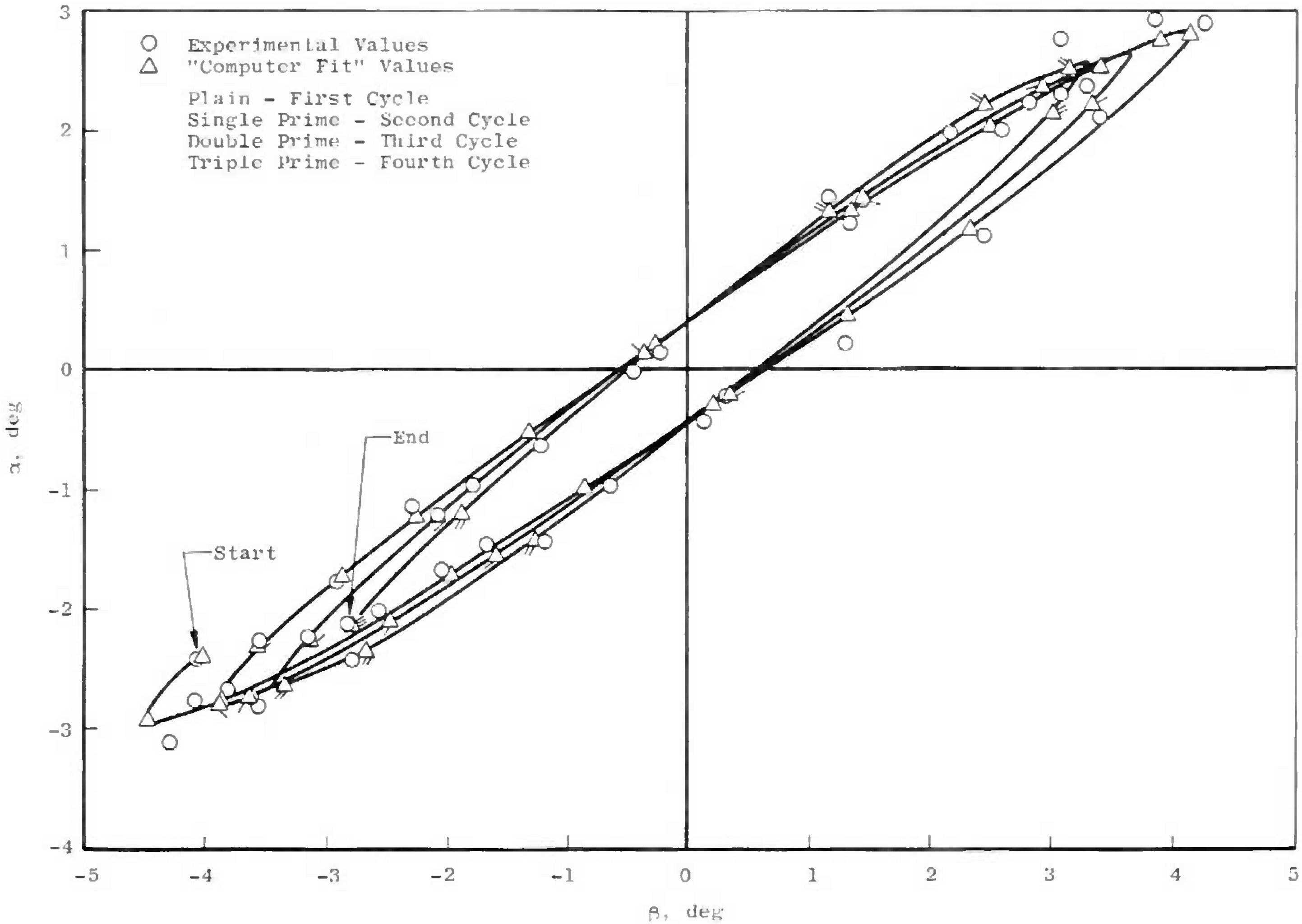
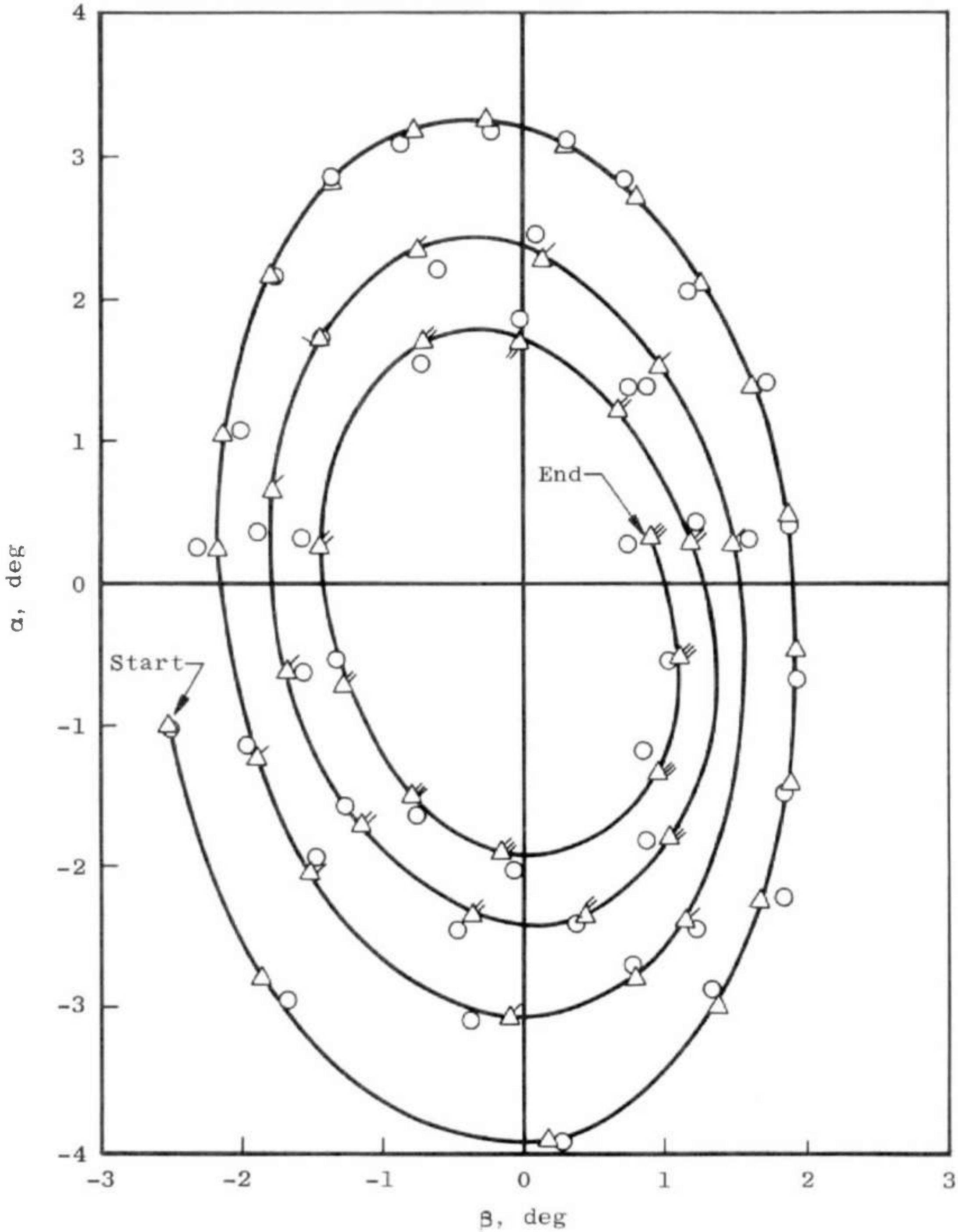


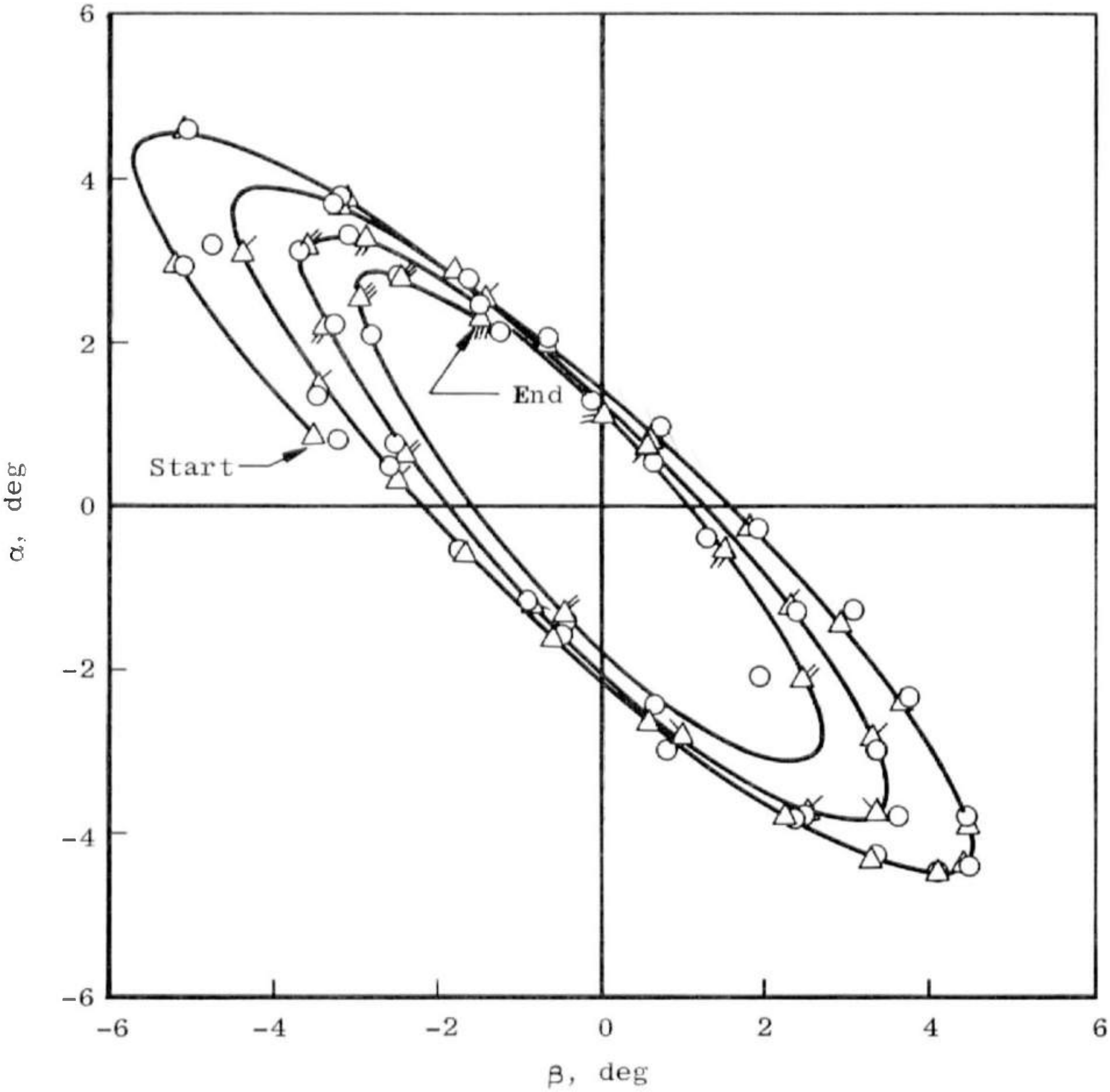
Fig. 6 Damping Derivatives



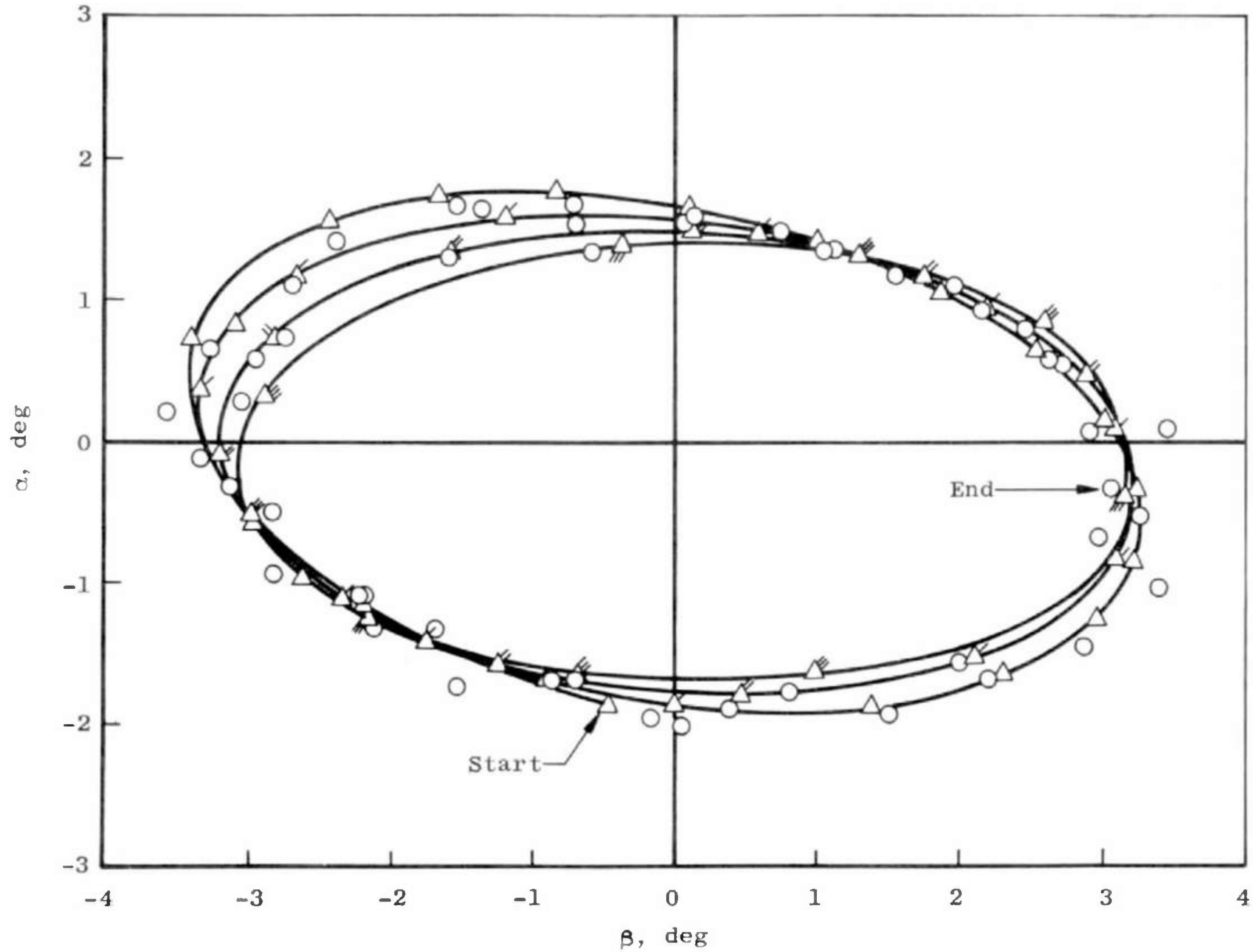
a. Shot No. 1 (Nonablating)
Fig. 7 Angular Motion Patterns



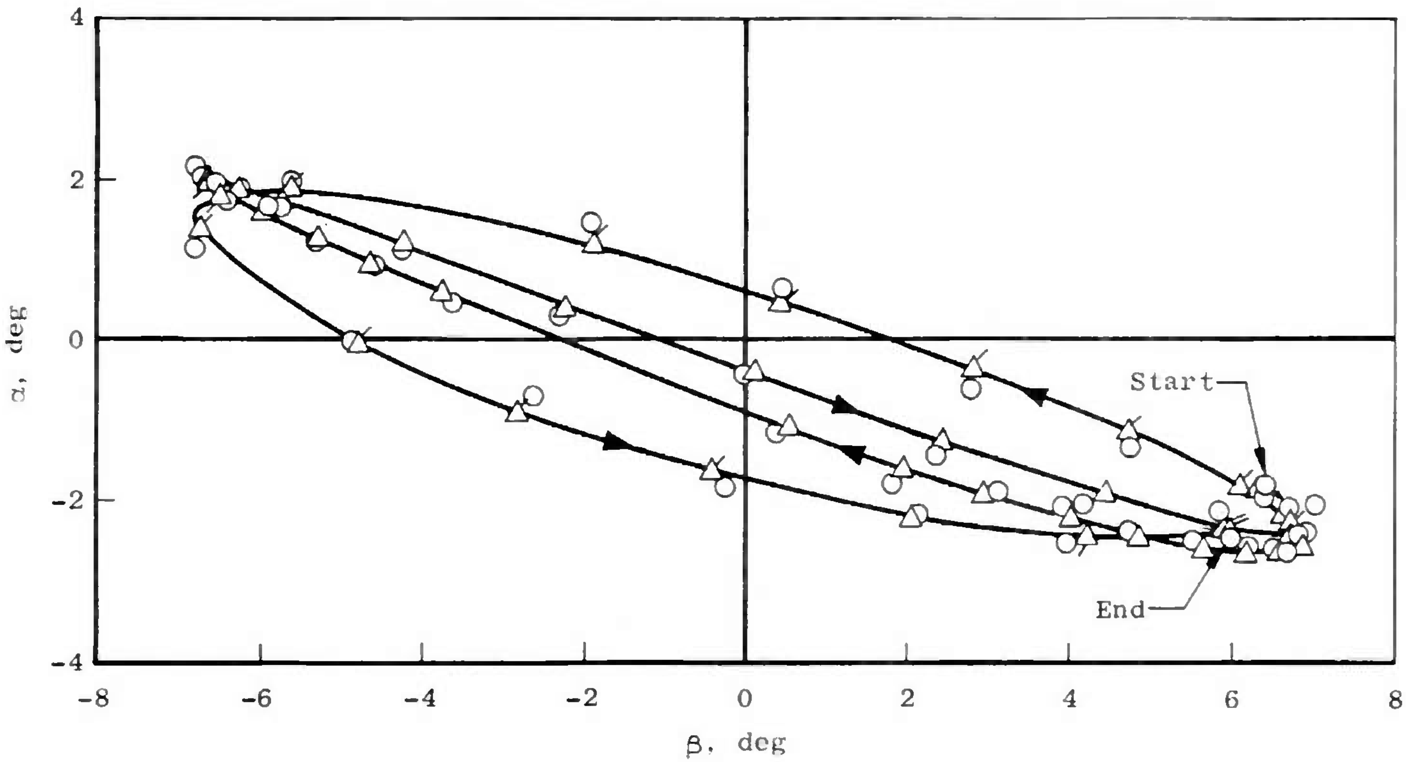
b. Shot No. 2 (Fore Sleeve)
Fig. 7 Continued



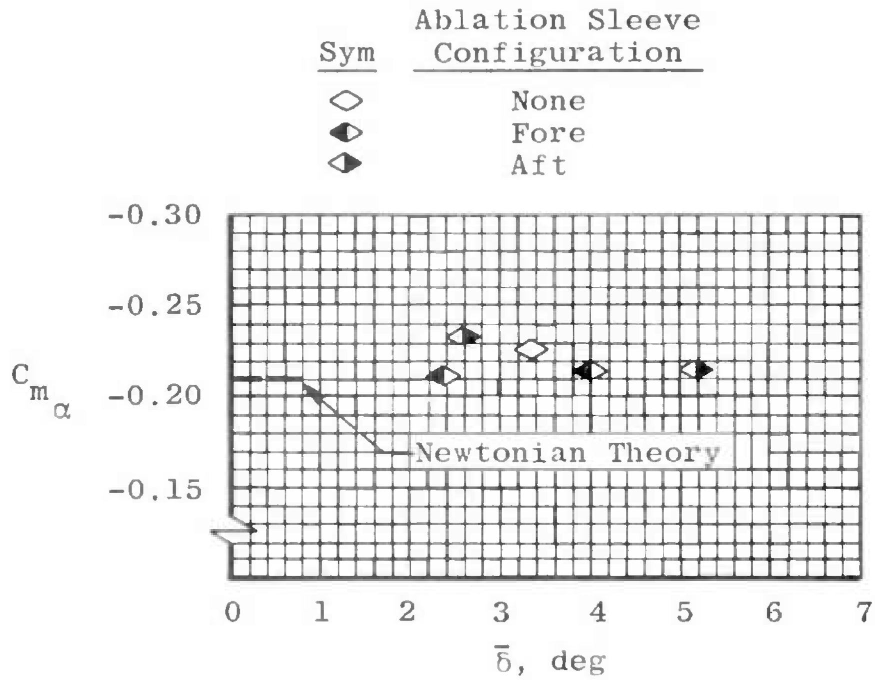
c. Shot No. 3 (Fore Sleeve)
Fig. 7 Continued



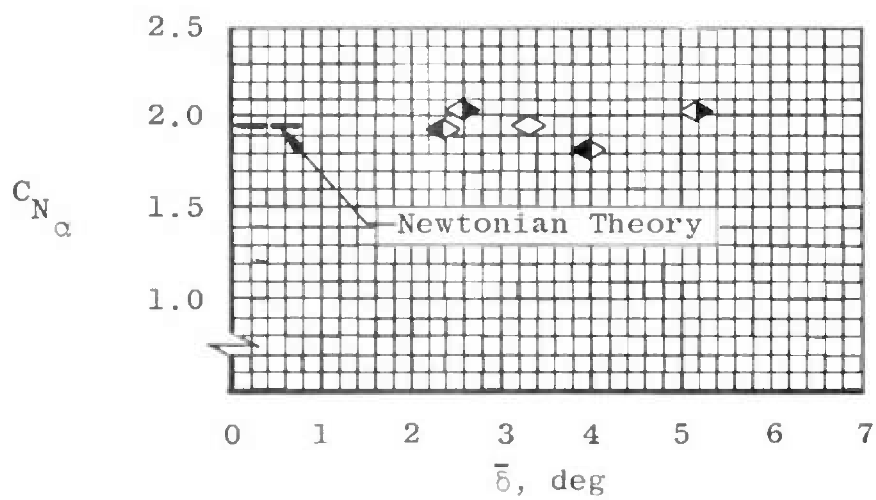
d. Shot No. 4 (Aft Sleeve)
Fig. 7 Continued



e. Shot No. 5 (Aft Sleeve)
Fig. 7 Concluded



a. Static-Stability Derivative
(Moment Reference = 0.63 ℓ)



b. Normal-Force Derivative

Fig. 8 Static-Stability and Normal-Force Derivatives

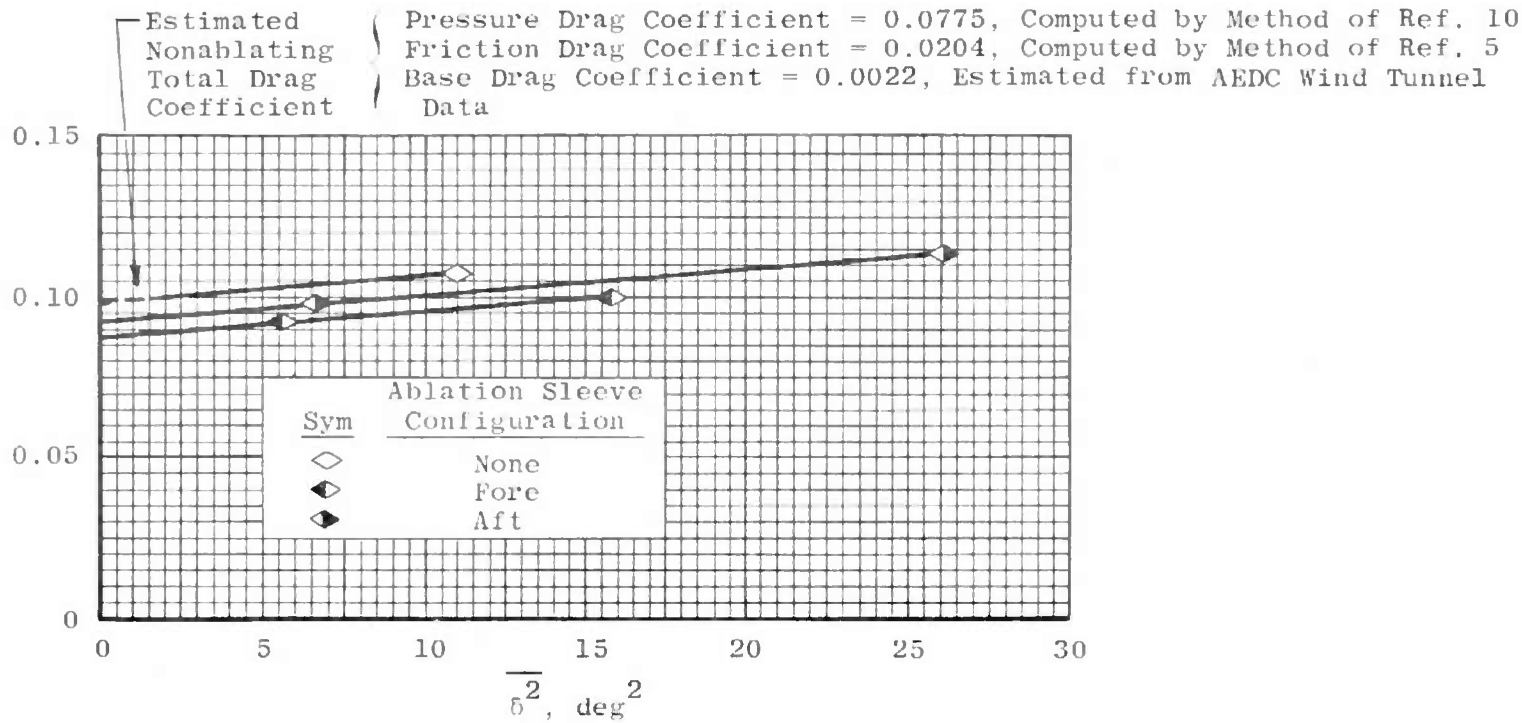


Fig. 9 Drag Coefficient

TABLE I
TEST CONDITIONS AND PHYSICAL CHARACTERISTICS OF THE CONES INVESTIGATED

Shot No.	Ablation Sleeve Configuration	M	$Re_{\ell} \times 10^{-6}$	Range Pressure, mm Hg	p^*, deg/ft	$\omega d/2V$	m, gm	cg^{**}	$I_y \times 10^4$ in.-lb-sec^2	$I_x \times 10^4$ in.-lb-sec^2
1	None	13.44	0.537	20.0	0.089	0.00109	21.50	62.96	0.539	0.106
2	Fore	13.25	0.531	20.0	0.052	0.00109	18.93	63.02	0.499	0.092
3	Fore	13.59	0.550	20.2	-0.010	0.00105	19.87	63.11	0.535	0.098
4	Aft	13.88	0.555	19.9	-0.078	0.00118	16.07	62.93	0.492	0.085
5	Aft	13.83	0.558	20.0	0.054	0.00072	24.42	65.00	0.598	0.115

*Measured Roll Rate

**Percentage of Model Length as Measured from the Nose

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13. ABSTRACT

A 1000-ft aeroballistics range was used to obtain free-flight stability and drag data for slightly blunted 10-deg semiangle cones with and without ablation occurring on the conical skirts. The configurations investigated included ones having fore- and aft-positioned ablation sleeves, as well as one with a skirt material which did not ablate. The investigation was conducted for a Mach number near 14 and a Reynolds number, based on cone length and free-stream conditions, of about 0.55 x 10^6. Measurements indicate that the forward ablation sleeve configuration investigated had an appreciably larger damping moment than the non-ablating cone, whereas the aft sleeve configuration had an appreciably smaller damping moment. Further, the ablating sleeves caused a decrease in the drag coefficient of up to 10 percent, but had no appreciable effect on the static moment and normal-force derivatives.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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ablation						
stability						
aeroballistic ranges						
hypervelocity flow						

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